

Transport properties of the hot and dense sQGP

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Abstract. The transport properties of the quark gluon plasma (QGP) are studied in a QCD medium at finite temperature and chemical potential. We calculate the shear viscosity $\eta(T, \mu_q)$ and the electric conductivity $\sigma_e(T, \mu_q)$ for a system of interacting massive and broad quasi-particles as described by the dynamical quasi-particle model “DQPM” at finite temperature T and quark chemical potential μ_q within the relaxation time approximation. Our results are in a good agreement with lattice QCD at finite temperature and show clearly the increase of the transport coefficients with increasing T and μ_q . Our results provide the basic ingredients for the study of the hot and dense matter in the Beam Energy Scan (BES) at RHIC and CBM at FAIR.

1. Introduction

The exploration of the phase diagram of strongly interacting matter is a major field of modern high-energy physics. The transition from a hadronic to a partonic medium at small net-baryon densities is known to be a crossover. At high baryon densities one expects new phases of the strongly interacting matter. Besides the understanding of the thermodynamic properties of such systems, the transport properties at high temperature and density are of interest for many purposes. They are the key ingredients for hydrodynamic calculations (η/s , ξ/s) and transport simulations which compare the in and out-of-equilibrium systems. They are also useful to confront different transport models, which study the expansion of the plasma created in relativistic heavy-ion collisions.

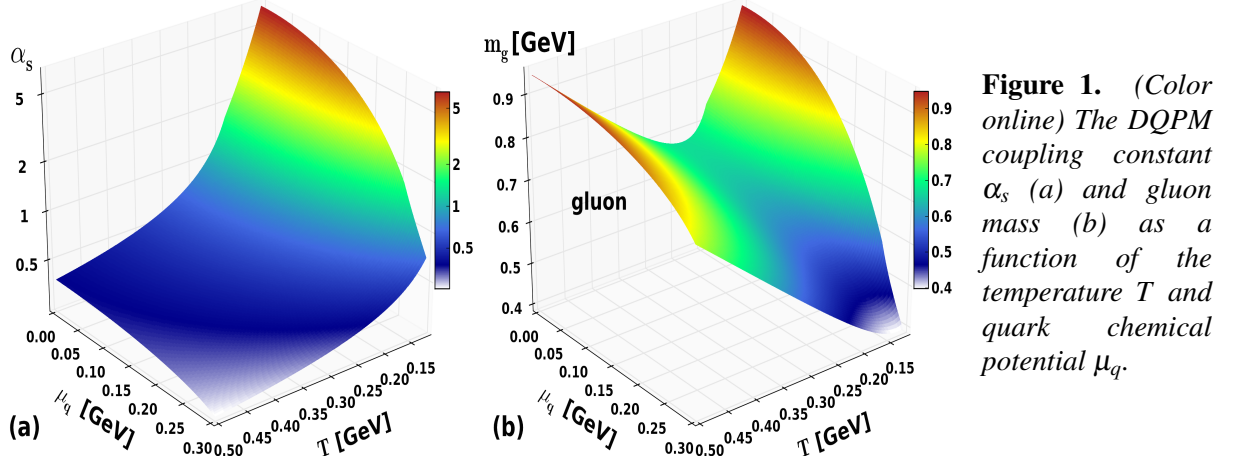
It is the purpose of this study to evaluate the transport coefficients for a system of interacting massive and broad quasi-particles as described by the dynamical quasi-particle model “DQPM” at finite temperature T and quark chemical potential μ_q within the relaxation time approximation. The relaxation times for these particles are calculated using the transition rates corresponding to qq , $q\bar{q}$, qg , gg elastic and $gg \leftrightarrow q\bar{q}$ inelastic scattering processes, where q (\bar{q}) denotes the light (anti-)quark and g the gluons of the sQGP.

2. The DQPM at finite (T, μ_q)

To evaluate the transition rates and cross sections of the partonic scattering processes in the sQGP using the leading order Born Feynman diagrams one needs to specify- in such a finite T and μ_q medium- the values of the fundamental ingredients which are the coupling α_s , the infrared regulator “IR” and the masses of external q, \bar{q} and g legs. These ingredients are provided by the DQPM in our calculations.

The DQPM coupling constant and gluon mass (which is considered also as IR) are shown in figure 1 (a) and (b) as a function of T and μ_q . One sees that α_s is much larger than one near $T_c(\mu_q)$; the non-perturbative effects then become most apparent at these temperatures. The increase of μ_q leads to a

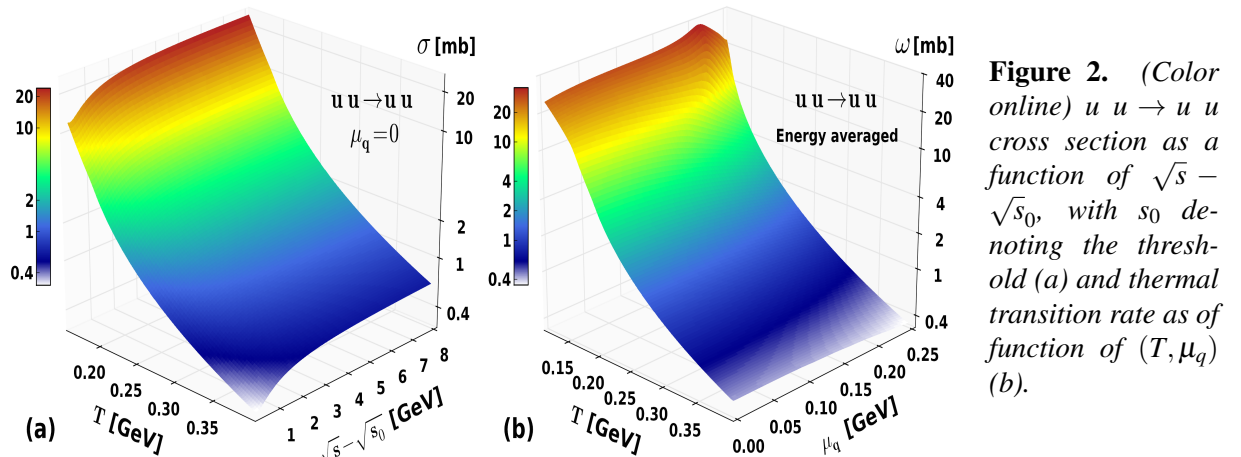
decrease of α_s and $m_{q,\bar{q},g}$. The DQPM provides also the particle width γ and the Breit-Wigner spectral function ρ^{BW} since the constituents of the sQGP are considered as strongly interacting massive effective quasiparticles [1].



3. g, q and \bar{q} scattering at finite (T, μ_q)

By dressing the quark and gluon lines with the effective propagators at finite temperature and chemical potential, we derive the on- and off-shell cross sections and transition rates for the dominant partonic reactions in the sQGP. The partons are dressed by effective DQPM pole masses in the on-shell case and are dressed by the DQPM spectral functions with a finite width in the off-shell case. We refer to the on-shell study by DpQCD approach (Dressed pQCD) and to the off-shell case by IEHTL approach (Infrared Enhanced Hard Thermal Loop) [2, 3].

The effect of the spectral function in the off-shell approach is demonstrated to be small because of the small DQPM width [2, 3]. However the off-shell IEHTL calculation shows a reduction of the kinematic threshold as compared to the DpQCD on-shell non-perturbative approach. Such an effect leads only to a small shift in the partonic transition rates. Therefore, we show in Figs.2 (a) and (b) the DpQCD $u u \rightarrow u u$ cross section σ as a function of T and $\sqrt{s} - \sqrt{s_0}$ (s_0 is the energy threshold) and transition rate ω as a function of T and μ_q , respectively.



Figs.2 (a) and (b) show a large enhancement of σ and ω for T close to $T_c(\mu_q)$ due to the infrared enhancement of $\alpha_s(T, \mu_q)$ as seen in Fig.1. Despite the lower value of the IR regulator at higher values of μ_q the smaller value of α_s at finite μ_q explains the decrease of σ and ω at finite and large μ_q .

The thermal transition rate ω can be parametrized by a power law in T for each value of μ_q . Having almost the same power laws at finite μ_q as compared to $\mu_q = 0$ for temperatures larger than $T_c(\mu_q = 0)$, we observe some scaling effects in the transport coefficients at these temperatures.

4. sQGP transport properties at finite (T, μ_q)

We compute transport coefficients using the relaxation time approximation. In the dilute gas approximation the relaxation time τ is obtained for on-shell particles $(\tau_c^{-1})_{\text{DpQCD}}$ and for off-shell quasi-particles $(\tau_c^{-1})_{\text{IEHTL}}, (\tau_c^{-1})_{\text{DQPM}}$ by Eq.(1) [4], where n_i is the q/\bar{q} or g density. For the DQPM we do not need the explicit cross sections since the inherent quasi-particle width $\gamma_i(T)$ directly provides the total interaction rate [1].

$$\begin{aligned} (\tau_i^{-1})_{\text{DpQCD}} &= \sum_{j \in q, \bar{q}, g} n_j^{\text{on}}(T, \mu_j) \omega_{ji}^{\text{DpQCD}}(T, \mu_j), \quad n_j^{\text{on}}(T, m_j, \mu_j) = \int \frac{d^3 p}{(2\pi)^3} f_j(p, T, m_j, \mu_j), \quad (\tau_i^{-1})_{\text{DQPM}} = \frac{\hbar c}{\gamma_i(T, \mu_i)} \\ (\tau_i^{-1})_{\text{IEHTL}} &= \sum_{j \in q, \bar{q}, g} n_j^{\text{off}}(T, \mu_j) \omega_{ji}^{\text{IEHTL}}(T, \mu_j), \quad n_j^{\text{off}}(T, \mu_j) = \iint \frac{d^3 p}{(2\pi)^3} \rho_j^{\text{BW}}(m_j) dm_j f_j(p, T, m_j, \mu_j). \end{aligned} \quad (1)$$

Figs. 3-(a) and (b) show the u -quark and gluon relaxation times for on- and off-shell partons at finite T and finite (T, μ_q) , respectively. Figs. 3-(a) shows that τ decreases with temperature since the quark and gluon densities are increasing functions of temperature. We can evaluate -in terms of powers of T - the behavior of $\tau_{u,g}$ for the different approaches. The higher power coefficients in the relaxation time for $T < 1.2T_c$ in DpQCD/IEHTL approaches can be traced back to the infrared enhancement of the effective coupling. A finite μ_q increases smoothly τ_u especially close to $T_c(\mu_q)$, as shown in Fig. 3-(b)

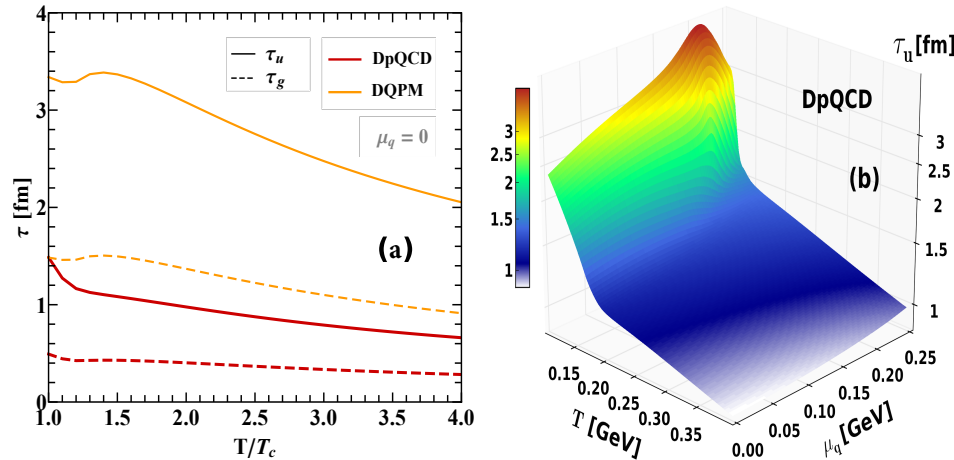


Figure 3. (Color online) u -quark and gluon relaxation times $\tau_{u,g}$ following the on- and off-shell models as a function of temperature T for $\mu_q = 0$ (a) and τ_u given by DpQCD as a function of (T, μ_q) (b).

Using the relaxation times τ shown above we compute the different transport coefficients of the sQGP. As an example we show the shear viscosity η and electric conductivity σ_e as a function of (T, μ_q) following our models where η and σ_e are given (for the case of on-shell partons) by

$$\begin{aligned} \eta^{\text{on}}(T, \mu_q) &= \frac{1}{15T} g_s \int \frac{d^3 p}{(2\pi)^3} \tau_s^{\text{on}} f_s \frac{\mathbf{p}^4}{E_s^2} + \frac{1}{15T} \frac{g_q}{6} \int \frac{d^3 p}{(2\pi)^3} \left[\sum_q \tau_q^{\text{on}} f_q + \sum_{\bar{q}} \tau_{\bar{q}}^{\text{on}} f_{\bar{q}} \right] \frac{\mathbf{p}^4}{E_q^2}, \\ \sigma_e^{\text{on}}(T, \mu_q) &= \sum_{f, \bar{f}} \frac{e_f^2}{m_f(T, \mu_q)} n_f^{\text{on}}(T, \mu) \tau_f^{\text{on}}(T, \mu_q), \end{aligned} \quad (2)$$

with e_q the electric charge of quarks. For off-shell partons Eqs.(2) can be generalized by taking into account the parton spectral functions, off-shell relaxation times and parton densities. Figs.4-(a) and (b) show that η/s , where s is the DQPM entropy density, and σ_e/T given by DpQCD/IEHTL and DQPM models are in the range of the lQCD data. On the other side -going from pQCD to non-perturbative based

models— leads to a reduction of η/s and σ_e/T . As a function of temperature η/s shows a minimum around T_c and then increases slowly for higher temperatures. σ_e/T increases slowly until it reaches at high temperatures the pQCD regime where $\sigma_e/T \sim \text{const.}$

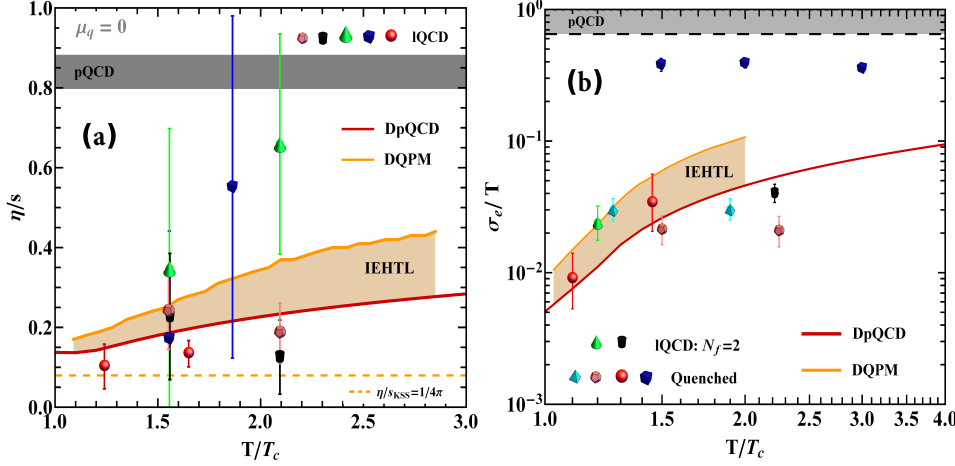


Figure 4. (Color online) η/s (a) and σ_e/T (b) following the on- and off-shell models as a function of temperature T for $\mu_q = 0$. The lattice QCD data are given from [5].

Finally the (T, μ_q) dependencies of η/s and σ_e/T are shown in Figs.5-(a) and (b) respectively. One sees that η increases like T^3 for large temperature for all chemical potentials in such a way that η/s is almost constant. η/s and σ_e/T show a smooth increase as a function of (T, μ_q) .

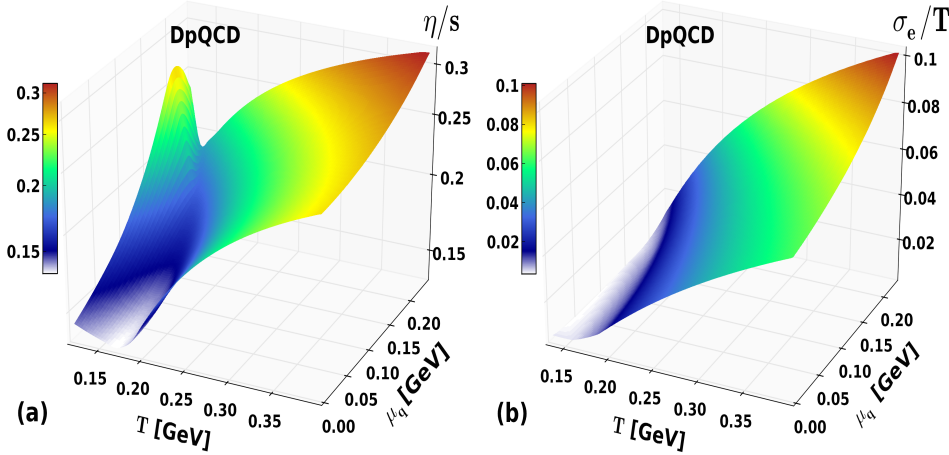


Figure 5. (Color online) η/s (a) and σ_e/T (b) following the on-shell DpQCD model as a function of (T, μ_q) .

5. Summary

We have presented a microscopic computation of sQGP transport properties at finite temperature and chemical potential using the relaxation times of the constituents of the system. The partons are considered as strongly interacting massive quasi-particles described by the DQPM [1–3] in which quarks and gluons have a finite mass and width that vary with T and μ_q . We have demonstrated that our η/s and σ_e/T are in the range of IQCD data. The transport coefficients in our models show a smooth dependence on (T, μ_q) . This is consistent with a crossover transition at small μ_q in line with lattice calculations.

References

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